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AN EXPERIMENTAL APPROACH TO THE CALCULATION OF CO_2 AMOUNT EVOLVED FROM SEVERAL SOILS

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INTRODUCTION

Circulations of bio-elements in ecosystem are earnestly studied in recent decades. Carbon and nitrogen in the terrestrial ecosystem, and nitrogen and phosphorus in the aquatic ecosystem are the main objects for those studies.

The carbon circulation is the largest one of the circulations of bio-elements in the terrestrial ecosystem. In order to estimate the circulation quantitatively, the rate of carbon assimilation by plants, the rate of carbon loss from plants, and the amount of organic carbon in soils have usually been taken into consideration (26, 41, 42). Only a few investigators, however, have paid attention to the return rate of carbon from soil to atmosphere, though the return rate should be clarified for demonstrating the matter circulation, especially production and decomposition, in the ecosystem.

The study of CO_2 evolution from soil was developed ecologically by Lundegårdh (30, 31), and microbiologically by Waksman (60) and Starkey (54, 55). In recent years there were published several excellent studies by Walter and Haber (63), Haber (16), Lieth and Ouellette (29), and Monteith *et al.* (36). In the latter there was a critical mistake of the technique as discussed by Haward (17).

Various techniques have been developed to measure the rate of CO_2 evolution from soils. They can be classified into the following three groups . i) Manometer method. Soil or litter sample is carried into the laboratory from the field. After treatment with water, nutrients or manure, the rate of CO_2 evolution from the sample is measured with a manometer (8, 15, 18, 44, 45, 53, 56). ii) Closed box method. After the treatment, a portion of sample soil is placed in an air-tight vessel. The evolved CO_2 is absorbed in alkaline solution and determined by titration (2, 4, 6, 9, 11-13, 19, 33, 37, 39, 43, 47, 49–52, 56, 59, 61). iii) Inverted box method. A large box is placed invertedly on the soil surface in the field. The CO_2 evolution rate is determined from the change of CO_2 concentration in the box or from the decrease of alkalinity (17, 25, 27, 29–31, 36, 37, 48, 62, 63, 66, 67).

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Although quite recently the aerodynamic procedure is under development for direct estimation of CO_2 flux in the field, the third technique seems to be the most preferable of the three from the ecological point of view. It has, however, some difficulties in finding general relationships between the evolution rate and environmental factors, because in the field the relationships are often disturbed by many complicated factors which make the activities of soil microbes and gas diffusion much fluctuating. Moreover, it is an unsolved problem how to treat the respiration of plant roots *in situ*.

In the present study the closed box method was mainly used for convenience' sake. The CO_2 flux was calculated for different soils with different vegetations of several places in central Japan. In this calculation the relationships between the CO_2 evolution rates and the soil properties were used. The main factors which influence the CO_2 evolution from the soil are temperature, moisture, quality and quantity of organic matter and structure of the soil. In this paper special concern was paid to the temperature, water content and organic carbon content of the soil.

Organisms in soil were left untouched in the present study. In soil, there live uncountable number of organisms with various modes of life. Aerobic and heterotrophic organisms get energy to support their activities by changing carbon compounds ultimately into CO_2 and water. As far as this essential reaction is concerned, the difference of species is not so important a matter as generally believed. In the discussion on the amount of CO_2 evolved from the soil it may be allowed to take the whole process, through which CO_2 is produced from various carbon compounds, as a black box. Many complex changes should be induced in the black box by a slight fluctuation of the environmental factors. As a result of these changes the CO_2 evolution rate may vary not a little. The purpose of the present study is to investigate not each change in the black box, but the quantitative relation between the changes of environmental factors and the outcome from the chain reactions which are brought about by the changes.

MATERIALS

The sample soils used in the present study and the outlines of sampling stands were as follows.

i) *Kawatabi Humic Allophane soil.* Kawatabi grassland is situated about 55 km north from Sendai in northern Honshu. Annual mean air temperature was 9.2°C, which was calculated from the data obtained at the Narugo Meteorological Station near the grassland. Soil was sampled in a *Miscanthus sinensis* community at ca. 600 m in altitude late in July, 1966. The soil was originated from volcanic ashes erupted by Mt. Kurikoma, distinguished by amorphous clay, allophane, and black-colored with a large quantity of humus. Annual production of the plant community in this area is being investigated by some workers as a part of International Biological Program.

ii) *Kirigamine Humic Allophane soil.* Soil was sampled at 1650 m in altitude in

Kirigamine montane grassland in Nagano Prefecture, central Honshu in June, 1964. In this place annual mean air temperature was 4.6°C. The soil was of the same kind as Kawatabi soil but the vegetation was different. *Arundinella hirta* was the dominant species, and *Scabiosa japonica* and *Carex* sp. had high cover degree as well. The vegetation was studied by Midorikawa, Iwaki, Hogetsu and Monsi (20, 34, 38). Although some parts of the grassland under better site conditions were covered with *M. sinensis*, the stand where soil was sampled was somewhat meagre. This place was covered with snow from December through March. It was reported that annual litter supply was 420 g dry weight/m² (38).

iii) *Northern Yatsugatake Brown Forest soil.* Sample soil was taken in June, 1965 at 2250 m in altitude in the northern part of the Yatsugatake Mountains, mountain range of dead volcanoes, in Nagano Prefecture. The annual mean air temperature observed from 1963 through 1965 was 1.8°C. This place was usually covered with snow from November through April. The vegetation was subalpine coniferous forest, where *Abies Mariesii* was the dominant. The soil surface was covered with moss, mainly *Pleurozium Schreberi*, and on the moss carpet *Pteridophyllum racemosus* grew almost exclusively. In this site, the soil developed about 30 cm in depth, and below that there lay parent rock of andesite and its debris. Kimura (24) reported that annual litter supply was 490 g/m².

iv) *Tonegawa Alluvial soil.* Soil was sampled in October, 1965 at a river-beach of the Tonegawa River at Toride (ca. 40 km NE from Tokyo, ca. 40 m above the sea level) in Ibaraki Prefecture. The annual mean air temperature was estimated to be 13.7°C. The surface soil was often frozen in January and February. Dominant species in this stand was *Solidago altissima* (naturalized), and *Miscanthus sacchariflorus* and *Equisetum palustre* were also observed. This stand was flooded after heavy rains twice a year or so in summer and autumn. Annual organic matter supply to soil surface was estimated to be quite high, 1780 g/m² (21).

v) *Koishikawa Kantô Loam volcanic ash soil* (Kaolinic Orthoelvium). The soil was sampled from a nursery for flowering plants of the Koishikawa Botanical Gardens in Tokyo in April, 1966. Soils were fertilized and plowed about 25 cm deep, and there was no litter on the surface. The annual mean air temperature in Tokyo was 14.7°C.

vi) *Chiba Kantô Loam volcanic ash soil.* Sample soil was taken in December, 1965 at a small forest of *Pinus Thunbergii*, 11–14 years old, in the campus of Chiba University. The stand was situated at about 10 m in altitude and the annual mean air temperature in Chiba was 14.9°C. The main species growing on the forest floor were *Miscanthus sinensis* and *Imperata cylindrica*. This place was bare 25 years ago, but since 1947 the pine trees invaded into the *Miscanthus-Imperata* community (40). The amount of annual litter fall was estimated to be 1200 g/m² (23).

vii) *Futtsu Sandy soil.* Futtsu sand bank, in Chiba Prefecture, fronts on the Tokyo Bay. *Pinus Thunbergii* was planted as windbreak. The annual mean air temperature was estimated to be 15.2°C. Sample soil was taken in February 1966 at a sand dune where the pine trees of 13 years old were growing relatively well. No

forest-floor vegetation was developed with a large amount of litter accumulation. Under the litter horizon, there existed crushed organic matter horizon in 2–4 cm thickness. Mycelia were developed conspicuously. The amount of annual litter supply was 1060 g/m² (23).

These six stands, except Ko'shikawa Botanical Gardens, were the places where the productivity of the plant community was studied or was being studied. Fig. 1 and Table 1 show the positions of the stands and monthly mean air temperature in each place.

Fig. 1. Stations where the soil was sampled.

Table 1. Monthly and annual mean air temperatures in each stand.

Month	Kawatabi	Kirigamine	N. Yatsu-gatake	Tonegawa	Koishikawa	Chiba	Futtsu
Jan.	−3.2	−8.4	−9.7	2.8	3.7	4.4	4.6
Feb.	−1.9	−8.6	−11.7	3.5	4.3	5.4	5.0
Mar.	0.6	−4.2	−8.6	6.6	7.6	8.0	8.0
Apr.	7.0	3.0	2.0	12.1	13.1	13.8	13.4
May	11.6	7.9	6.1	16.6	17.6	17.4	17.8
Jun.	15.9	13.4	9.9	20.1	21.1	20.7	21.3
Jul.	21.3	16.5	14.0	24.2	25.1	24.6	25.5
Aug.	22.2	17.8	15.1	25.5	26.4	26.3	26.8
Sep.	18.0	13.7	9.7	22.3	22.8	23.0	23.6
Oct.	12.0	8.3	3.7	14.9	16.7	16.9	17.5
Nov.	5.3	2.6	−2.2	10.5	11.3	11.7	12.3
Dec.	−0.6	−6.5	−6.5	5.3	6.1	7.0	7.0
Annual mean	9.2	4.6	1.8	13.7	14.7	14.9	15.2

METHODS

At each sampling, plant tops and litter were removed and soil was taken to a depth of 5 cm in a rectangle of 2 m×1 m. Then large fragments of organic matter, including plant root, and gravel were eliminated. Sample soil put in polyethylene bags was brought to the laboratory. Water content, maximum water holding capacity and pH values were measured with a small quantity of the sample soil taken from each bag.

A modified measuring apparatus which was designed originally by Prof. Y. Saijo of Nagoya University for analysis of carbonate in water, was employed. This apparatus was made with two marketing plastic vessels of different size (Fig. 2). Sample soil of 250–400 g in fresh weight was contained in the larger vessel ; 148 mm in diameter, 87 mm in depth and 1. 5 l in volume. The smaller one had a diameter of 77 mm, a depth of 22 mm and eight holes of 4 mm in diameter in the side wall. The air-tight lids of the two vessels were made from vinyl-chloride. The lid of the smaller one was stuck to the inside of the lid of the larger one with heated soldering iron to hang the vessel itself. In the smaller vessel, 10–20 ml of 0. 5 N NaOH solution was put for CO_2 absorption. Deionized water was added to the sampled soil dried in air for a week in the large vessel to get a certain water content level. The lid was put on the vessel and closed with vinyl tape. The apparatus were left in the dark at constant temperatures of i) 10±2°C in a refrigerator ; ii) 20±1. 5°C in an air conditioned room ; iii) 30±1. 5°C in an incubator. For the determination of CO_2 evolution, the larger lid was put off at intervals of 1–7 days, according to the amount of the evolved CO_2. Then 10–20ml of 0. 5 N $BaCl_2$ solution was added to the alkaline solution in the smaller vessel, in order to precipitate the carbonate as $BaCO_3$. The remains of the alkaline solution were titrated with standardized citric acid solution. The tests revealed that 10 ml of 0. 5 N NaOH solution is sufficient to absorb more than 25 mg carbon in the form of CO_2. Detection of very low CO_2 evolution rate is beyond the accuracy of the present method.

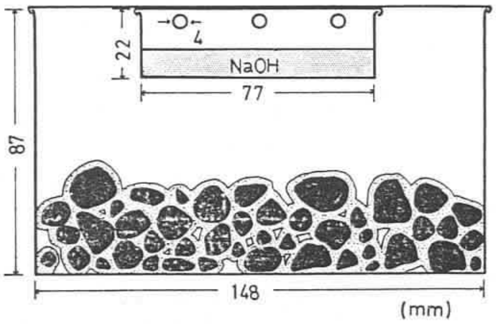

Fig. 2. Plastic apparatus for measurement of the CO_2 evolution rate.

Amount of water in the soil was determined by drying the sample to a constant weight at 108°C, and the maximum water holding capacity, by usual technique. In

the present study, water content was expressed in a percentage of the maximum water holding capacity. Organic carbon was measured by a modified Tyurin method, total nitrogen by the micro-Kjeldahl method, and total phosphorus by the Shelter-Happer's and the Truog-Meyer's methods. For the determination of pH values, sample soil was immersed in deionized water or 1 N KCl solution in a ratio of 1 : 2.5 in weight and a glass electrode pH-meter was used. Bulk density values were determined by drying a known volume of the field soil at 108°C. Specific gravities of the soil were determined with a pycnometer.

RESULTS

1. Examination of measuring apparatus

The amount of CO_2 which was absorbed by NaOH solution in the measuring apparatus was the sum total of CO_2 i) evolved from sample soil, ii) confined originally in the apparatus, and iii) entered into the apparatus during incubation period. The incursion rate of CO_2 into the apparatus from outside was measured five times repeatedly with ten apparatus at three different temperatures. The results are shown in Fig. 3. The incursion rate differed considerably according to the incubation temperature: 0.28, 0.39 and 0.44 mg C/apparatus/day, at 10°, 20° and 30°C, respectively. These rates corresponded to about 1/3 of the lowest rate of CO_2 evolution from sample soil.

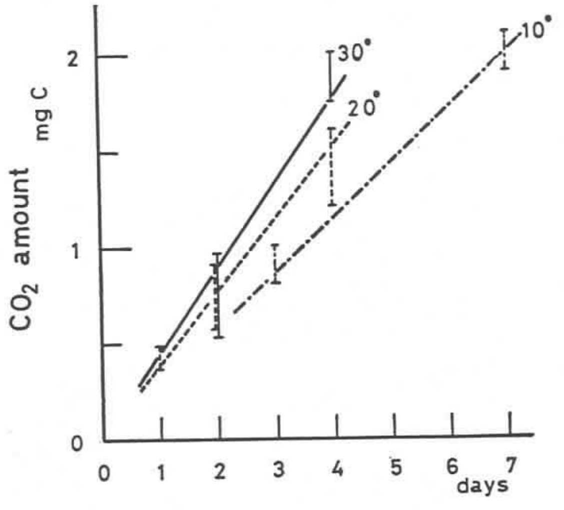

Fig. 3. Effect of temperature on the CO_2 incursion into the measuring vessel from outside.

Decrease of the pressure in the vessel attended with oxygen consumption by soil organisms was compensated by increase of vapor pressure. If the pressure inside the

vessel happened to differ from outside, the vinyl-chloride lid could be swollen or caved in about 3.5 % of total volume and such a move of the lid reduced the difference of pressure.

Equal weight of soil sampled at a stand was put separately in each of ten apparatus to determine the standard deviation of the CO_2 evolution rate at 20°C (Fig. 4). The deviation was large at the beginning of incubation period, but after ten days it settled a nearly constant value. The difference of each measuring apparatus and the variation of microflora in each apparatus seemed to be negligibly small.

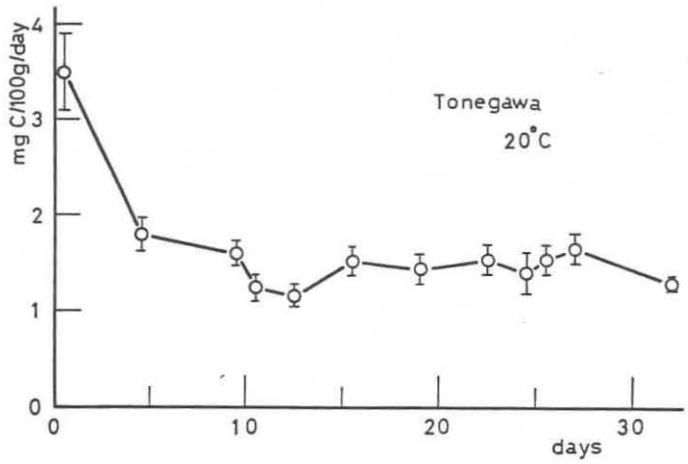

Fig. 4. Time trend curve of the CO_2 evolution rate at 20°C of Tonegawa Alluvial soil. Vertical lines represent 95% confidence limit of mean rate in each time.

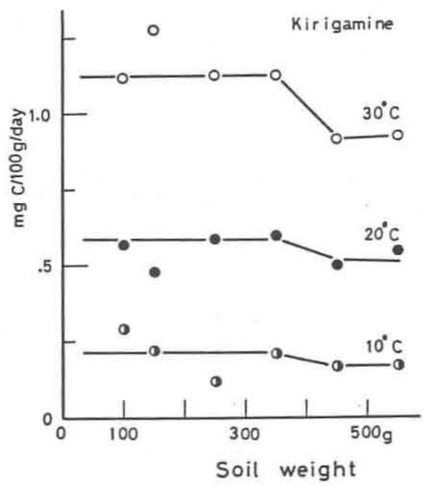

Fig. 5. CO_2 evolution rate in relation to the thickness of soil in measuring vessel at three incubation temperature with Kirigamine Humic Allophane soil.

It is an important matter that the quantity of sample soil in the apparatus should be limited, because the thickness of soil influences the rate of gas diffusion in soil. Kirigamine soil was put in the apparatus in six grades of fresh weight, from 100 g to 550 g. The thickness of sample soil in the vessel was from 1 cm to 5 cm. The mean rates of CO_2 evolution for 20 days, from 38th to 58th day of incubation, are shown in Fig. 5. Under all temperature conditions, the CO_2 evolution rates of the sample soils of above 450 g decreased gradually on a fresh weight basis. This apparently indicates that the exchange of oxygen for CO_2 in the deeper part became difficult. In the closed box method, the maximum quantity of sample soil should be determined beforehand.

When the evolution rate of CO_2 is measured by such a closed box method, the absorption efficiency for CO_2 of 0.5 N NaOH solution should be determined previously. This efficiency was gained by comparison with the aeration method. The lid of the vessel designed for the closed box method was changed for a lid that was prepared for aeration. Then the measuring apparatus was connected with an infrared gas analyzer, URAS, of Hartmann & Braun AG.

Tonegawa soil, Chiba soil and Futtsu soil were used for this test. The air stored previously in a reservoir was passed through the measuring apparatus immersed in a water bath at constant temperature, at a speed of 25 l/hr and in darkness. The increase of CO_2 concentration in the air which came through the apparatus was measured with URAS and the evolution rate was calculated. At the beginning of aeration the very high CO_2 concentration began immediately to decrease and attained to a constant value after ca. $^1/_2$–1 $^1/_2$ hrs. The high initial concentration seemed to be caused by the CO_2 accumulated in the course of preparation and that sucked out from the soil pore by the air flow. The CO_2 evolution rates thus obtained were compared with the rates determined by the closed box method on the previous day or on the next

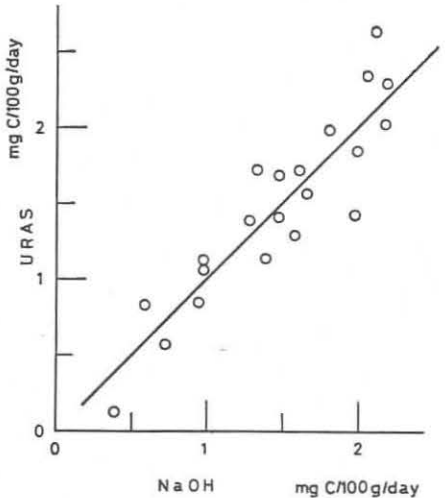

Fig. 6. Relationship between the CO_2 evolution rates measured by infrared gas analyzer(URAS)and those by 0.5 N NaOH solution, at 20°C in darkness.

day. The results are shown in Fig. 6. The relationship between both rates could be expressed by a regression equation, $Y=1.04\,X-0.04$. Ninety-five per cent confidence limits for the regression coefficient were ± 0.23.

The CO_2 evolution rate is largely affected by the disturbance of soil structure. In the present study it was assumed that the sample soil kept in the apparatus could take a similar structure to the natural one after 4–5 weeks. In another experiment, the CO_2 evolution rate was measured with a clod of soil sampled with slight disturbance of soil structure in the Tonegawa stand. The rate became stable by the 10th day. Any large difference was hardly observed between the CO_2 evolution rate from the soil sampled with heavy disturbance of soil structure, and that of the soil sampled with slight disturbance.

In the present experiments, the CO_2 evolution rates were measured with duplicate samples for each definite condition.

2. Chemical and physical properties of sample soils

The soil properties are shown in Table 2. Here the water content was shown on an oven-dry weight basis. The Brown Forest soil and the Humic Allophane soils of Kawatabi and Kirigamine were rich in humus; they were originated from volcanic ashes on the montane area. Organic carbon content (ca. 20 % on an oven-dry weight basis) and total nitrogen content (ca. 1 %) of these soils were much higher than those of the other soils. The difference between the value of pH (H_2O) and that of pH (KCl) was about one in each soil and it was smaller than in other soils. This might suggest that a large part of the total hydrogen ions were free in soil solution. The total phosphorus content was lower in Kawatabi soil than in the other humus-rich soils.

Koishikawa soil was fertilized for flowering plants, so that its total nitrogen and phosphorus contents were high. The ratio of carbon, nitrogen and phosphorus at the surface of the soil was 1 : 0.11 : 0.05.

At each stand of Tonegawa, Chiba and Futtsu, the content of organic carbon was far smaller than those in the above-mentioned montane soils, although a large amount of organic matter was supplied to soil surface from the plant communities. There were large differences in organic carbon content between these three soils. It is likely that the differences were caused not only by the mineralization rate but also by the leaching rate of carbon compounds in the process of decomposition, though Monteith *et al.* (36) described that loss of carbon by leaching could be ignored. The differences between the values of pH(H_2O) and pH(KCl) in these soils were large, especially in Sandy soil. Total nitrogen content of Sandy soil was considerably low, so that the organic carbon to nitrogen ratio in this soil was higher than in the other two soils.

Chemical analyses of each soil along the profile at the sampling time proved that organic carbon content and total nitrogen content were considerably higher in the surface soil than in the subsoil at the Tonegawa, Chiba and Futtsu stands. They

Table 2. Some properties of sample soils in different depth at sampling time (on an oven-dry weight basis).

Soil	Depth cm	Water content %	pH (H_2O)	pH (KCl)	Organic C %	Total N %	Total P %
Kawatabi							
Humic	0—5	163	5.2	4.1	18.8	1.03	0.087
Allophane	5—10	155	5.1	4.1	15.0	0.88	0.083
soil	10—15	141	5.3	4.2	12.4	0.74	0.071
Kirigamine							
Humic	0—5	160	4.7	4.1	19.2	1.11	0.215
Allophane	5—15	171	4.5	4.1	18.3	1.08	0.210
soil	20—25	168	3.9	3.8	17.5	1.02	0.207
N. Yatsugatake							
Brown Forest soil	0—5	241	4.5	4.1	20.2	1.32	0.167
Tonegawa							
Alluvial soil	0—5	47	6.7	5.2	1.34	0.128	0.072
	10—15	47			0.962	0.107	0.078
	15—20	53	6.8	4.9	0.939	0.100	0.065
	20—25	51			0.771	0.068	0.055
	25—30	44	6.6	4.9	0.611	0.057	0.046
	30—35	50	6.6	5.0	0.566	0.064	0.055
	35—40	53			0.499	0.045	0.046
	40—45	46			0.529	0.043	0.043
	45—50	47			0.584	0.051	0.055
Koishikawa							
Kantô Loam	0—5	69	6.1	5.1	3.81	0.431	0.191
soil	5—10	73			3.59	0.427	0.147
	10—15	73	6.2	5.2	3.79	0.345	0.206
	20—25	78	6.6	5.5	2.99	0.301	0.123
	30—35	90	6.1	5.2	2.27	0.230	0.110
	40—45	100			2.10	0.234	0.094
Chiba							
Kantô Loam	0—5	73	7.4	5.2	4.77	0.350	0.084
soil	5—10	82	7.3	5.3	1.85	0.193	0.062
	10—15	100	7.1	5.5	2.10	0.190	0.063
	15—20	111			1.87	0.169	0.060
	25—30	119			1.07	0.100	0.055
	30—35	116			1.05	0.110	0.053
Futtsu							
Sandy soil	0—5	4.5	7.4	4.6	0.453	0.015	0.018
	5—10	4.0			0.245	0.007	0.019
	10—15	3.8	7.6	4.5	0.188	0.006	0.016
	15—20	4.3			0.165	0.004	0.016
	25—30	4.1	7.4	4.8	0.120	0.003	0.016
	35—40	5.1			0.107	0.004	0.016
	50—55	4.6			0.141	0.005	0.015

decreased to about half of those in the surface soil at the depth of 10 or 20 cm, but total phosphorus decreased very slowly or almost no. Koishikawa soil was plowed before the sampling time, so the contents of these elements were homogenized through 20 cm depth. In Kirigamine soil the quantities of organic carbon and total nitrogen, which were very large at the surface, decreased slowly with depth to 40 cm. Below 40 cm organic carbon content became lower than 2 %. In the Northern Yatsugatake stand, it was impossible to take soil sample in each profile, because the parent rock was very close to the soil surface and *Abies* roots ran in upper profile quite densely.

The solids of the volcanic ash soils (Kawatabi and Kirigamine) were about 20 % of the total volume of the soil sample (Fig. 7). Water content of the humus-rich soils was more than 50 % of the total volume. The results indicate that humus-rich soils can involve large amount of water. In the humus-poor soils of Chiba and Koishikawa, air occupied about half of the pore space. The solid volume of the Alluvial soil was larger than that of the Sandy soil, and on the contrary, the reverse was observed in the water volume. In the Sandy soil, most of the space pore was occupied by air.

Surface soils were studied monthly at the Tonegawa, Chiba and Futtsu stands from the autumn of 1965 through that of 1966. In Table 3 are shown the soil properties and the amount of litter accumulated on the ground in each month.

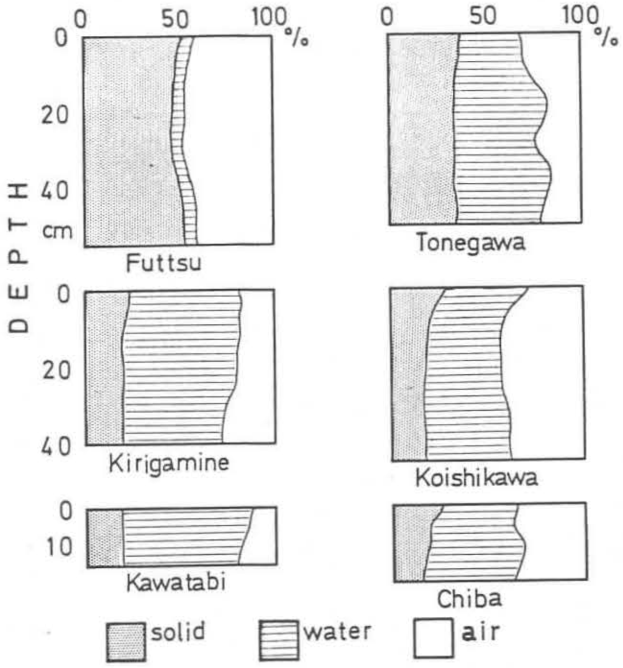

Fig. 7. Three phase structure of six types of soil at each sampling time.

Table 3. Seasonal changes of some properties of three types of soil in the early part of each month. Water content is expressed in a percentage of the maximum water holding capacity and the contents of organic carbon, total nitrogen and phosphorus are expressed on an oven-dry weight basis.

Month	Water content %	pH (H_2O)	pH (KCl)	Organic C %	Total N %	Total P %	Litter g/m^2
			Tonegawa Alluvial soil				
Oct.	50.1	6.4	4.6	1.27	0.127	0.067	3400
Nov.	51.8	6.3	4.9	1.36	0.143	0.072	3170
Dec.	55.9	6.5	4.7	1.51	0.151	0.048	1610
Jan.	53.8	6.5	4.9	1.46	0.160	0.069	1450
Feb.	48.8	6.6	4.8	1.46	0.146	0.075	930
Mar.	52.8	6.5	4.9	1.63	0.176	0.086	670
Apr.	51.1	6.8	5.1	1.61	0.176	0.087	640
May	52.6	6.4	4.7	1.73	0.182	0.078	450
Jun.	59.0	6.7	4.8	1.99	0.199	0.075	620
Jul.	61.7	6.6	4.9	1.45	0.157	0.074	530
Aug.	46.0	6.7	4.9	1.90	0.171	0.079	1500
Sep.	40.8	6.5	5.1	1.66	0.245	0.081	1580
			Chiba Kantô Loam soil				
Oec.	56.2	7.4	5.2	4.77	0.350	0.084	1100
Jan.	70.0	6.4	5.5	4.45	0.370	0.077	1300
Feb.	54.9	6.6	5.4	5.66	0.402	0.084	890
Mar.	58.1	6.4	5.6	4.93	0.415	0.094	990
Apr.	64.9	7.3	5.5	5.68	0.474	0.082	1080
May	62.9	7.1	5.9	5.54	0.427	0.099	780
Jun.	62.0	7.4	5.7	4.96	0.377	0.079	1020
Jul.	74.0	7.3	5.7	6.92	0.400	0.076	760
Aug.	38.0	6.5	5.1	6.68	0.428	0.087	800
Sep.	34.4	6.6	5.7	5.37	0.471	0.082	480
Oct.	53.4	6.8	5.1	5.15	0.514	0.090	1030
Nov.	57.1	6.7	5.4	4.98	0.451	0.088	980
			Futtsu Sandy soil				
Oct.	12.9	7.6	4.3	0.511	0.019	0.018	1420
Nov.	22.7	7.3	4.4	0.563	0.025	0.018	850
Dec.	14.1	7.7	4.2	0.584	0.024	0.019	1340
Jan.	22.7	7.1	4.6	1.04	0.039	0.020	1080
Feb.	12.8	7.4	4.6	0.453	0.015	0.018	1540
Mar.	60.0	5.9	4.3	2.73	0.116	0.023	1480
Apr.	32.8	7.6	4.3	0.982	0.036	0.018	2100
May	44.6	6.9	4.4	1.30	0.049	0.021	2080
Jun.	26.2	6.6	4.1	0.631	0.022	0.018	1860
Jul.	35.4	6.7	4.4	0.810	0.033	0.020	1150
Aug.	7.7	6.4	4.2	0.828	0.029	0.021	1730
Sep.	9.1	7.4	4.6	0.539	0.038	0.019	2080
Oct.	15.2	7.4	4.4	0.910	0.066	0.021	—

The organic carbon content of the soils fluctuated largely in the Chiba and Futtsu stands. The supply of organic matter, of which 40-50 % is carbon, to soil surface differed substantially with seasons. The most of litter fall occurred from September to November at the Tonegawa stand, in May, November and October at the Chiba stand, and in April and May at the Futtsu stand. In general, organic carbon content and total nitrogen content of soil had a trend to become larger toward summer. Some peaks and troughs were seen in total phosphorus content but the relation between the content and the season was not clear. Various inorganic salts are supplied to soil from vegetation and atmosphere by precipitation. But it is impossible to suppose that this large fluctuation was brought about by precipitation and leaching from tree crown (10, 32, 35). The Tonegawa River flooded in June and September in 1966, so that the sampling stand was covered with water about 1 m deep. The decreases of organic carbon and total nitorgen in July might be caused by the leaching. The content of total phosphorus did not show any marked change by the flood of the river water. Monthly fluctuations of pH values were a little.

3. Evolution rate of CO_2 in relation to water content

The water content of soil has a great influence on the mineralization of soil organic compounds. The increase of the amount of soil water is attended with the decrease of the volume of soil air. A certain amount of water was required for the maximum evolution of CO_2 by soil organisms (56). It was reported that 50–80 % of water holding capacity could give a maximum CO_2 evolution rate (1).

The relation between the CO_2 evolution rate and the water content has been investigated with the six types of soil. The maximum water holding capacities on an oven-dry weight basis were as follows: i) 210 % for Kirigamine Humic Allophane soil, ii) 300 % for Northern Yatsugatake Brown Forest soil, iii) 90 % for Tonegawa Alluvial soil, iv) 69% for Koishikawa Kantô Loam soil, v) 130% for Chiba Kantô Loam soil, and vi) 35 % for Futtsu Sandy soil.

At the beginning of the incubation period, the CO_2 evolution rate was very high in all sample soils. This phenomenon was recognized as "Drying effect" or "Birch's effect" (4, 53). There is also a report (45) that before the appearance of this effect lag phases were recognized in case that the air-dried sample soil was re-wetted. The CO_2 evolution rate decreased slowly with the lapse of time, as Newman and Norman (39), and Ino and Monsi (19) illustrated. After a few weeks, the evolution rate became constant. As for the sample soils with very low water content or under water-logged condition, the peaks at the beginning of incubation period were low and it took a comparatively short time to attain a constant evolution rate. The constant value was accepted as the "CO_2 evolution rate" in the present study. The CO_2 evolution rate increased with the water content of the soil within some limits and its maximum occurred when the water content was between 60 % and 80 % of water holding capacity. This phenomenon supported the view that the water content below 50 % is defficient for microbial activity and water content above 85% makes the aeration

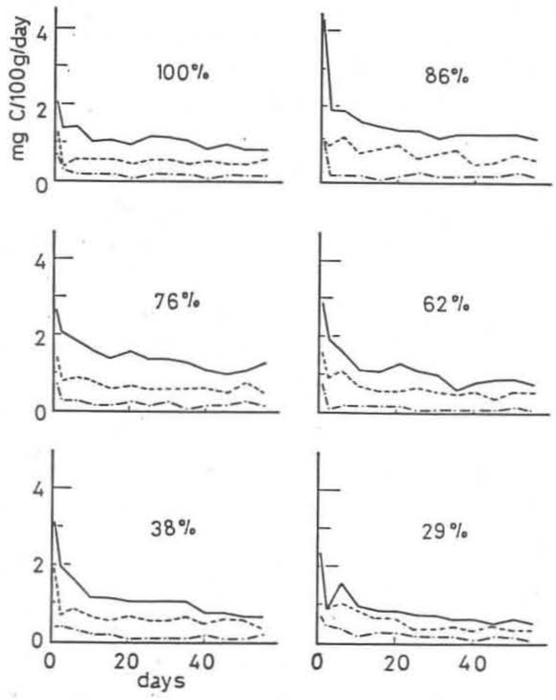

Fig. 8. Time trend curves of the CO_2 evolution rate of Kirigamine Humic Allophane soil at 10°C (— · — · —), 20°C (-----) and 30°C (———).

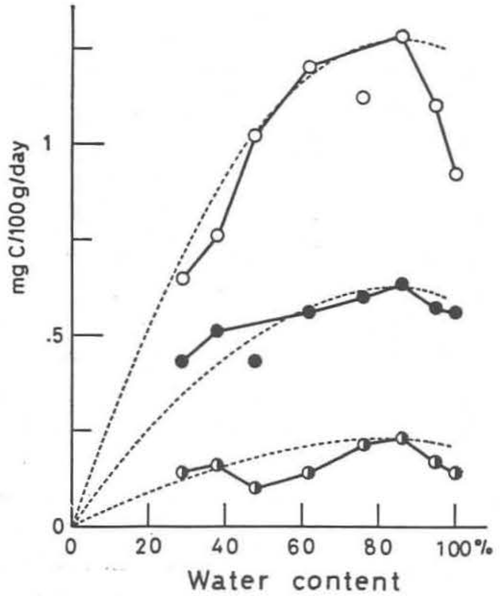

Fig. 9. CO_2 evolution rate in relation to water content with Kirigamine Humic Allophane soil at 10°C (—◑—), 20°C (—●—) and 30°C (—○—). Broken lines represent approximate curve of relationship between evolution rate and water content at each temperature.

unsufficient.

i) *Kirigamine Humic Allophane soil*

The time trend curves of the CO_2 evolution rates under various water (100, 86, 76, 62, 38, 29 %) and temperature (10°, 20°, 30°C) conditions are shown in Fig. 8. The evolution rate differed largely with the soil water content and was highest at 30°C and lowest at 10°C in all water conditions. The evolution rates became constant in a short period and the mean rates during 20 days (38th–58th day) were taken for the calculation of CO_2 flux from the soil surface. In Fig. 9 are shown the relations between the CO_2 evolution rates and the water contents of the sample soil at three different temperatures. These relations could be approximately expressed with common parabolas (broken lines), though these lines were not in accord with some measured values. Common parabola is convenient for calculation of CO_2 flux. At each temperature, the evolution rates took their maximum when the water content was 85 % (175 % on an oven-dry weight basis). These maximum rates were 0. 23, 0. 63 and 1. 28 mg C/100 g dry soil/day at 10°, 20° and 30°C, respectively.

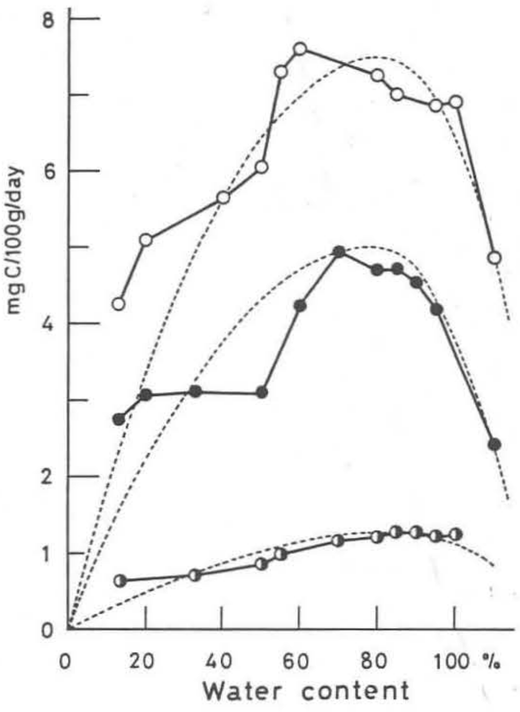

Fig. 10. CO_2 evolution rate in relation to water content with Northern Yatsugatake Brown Forest soil at 10°C (—◑—), 20°C (—●—) and 30°C (—○—). Broken lines represent approximate curve of relationship between evolution rate and water content at each temperature.

ii) *Northern Yatsugatake Brown Forest soil*

This soil contained a large amount of humus as Kirigamine soil did, but its CO_2 evolution rate was about five times as high as that of the latter. The water content of the sample soil at which the CO_2 evolution rate reached a maximum differed with incubation temperature: 90 % (270 % on an oven-dry weight basis) at 10°C, 70 % (210 %) at 20C°, and 60 % (180 %) at 30°C (Fig. 10). The maximum values were 1. 25, 4. 90 and 7. 60 mg C/100 g dry soil/day, respectively. In the early stage of incubation the CO_2 evolution rate was 10–15 mg C under the optimum condition and about 40 days after incubation it came to take a constant value. No large initial peaks appeared in the 10°C series. The evolution rate fluctuated in the 30°C series and it settled at a constant value after a long period. Super-optimum water content caused a slow decrease of the evolution rates. The water-logged condition, however, brought about a very small evolution rate and marked gleization in the lower part of sample soil in course of experiments. It appears that the diffusion of oxygen was checked by the water horizon on soil surface, as Greenwood (14) has reported that the changing-over from aerobic metabolism to anaerobic one could take place in several soils at an oxygen concentration of 3×10^{-6} M.

iii) *Tonegawa Alluvial soil*

In Fig. 11 are shown the time trend curves of the CO_2 evolution rates from

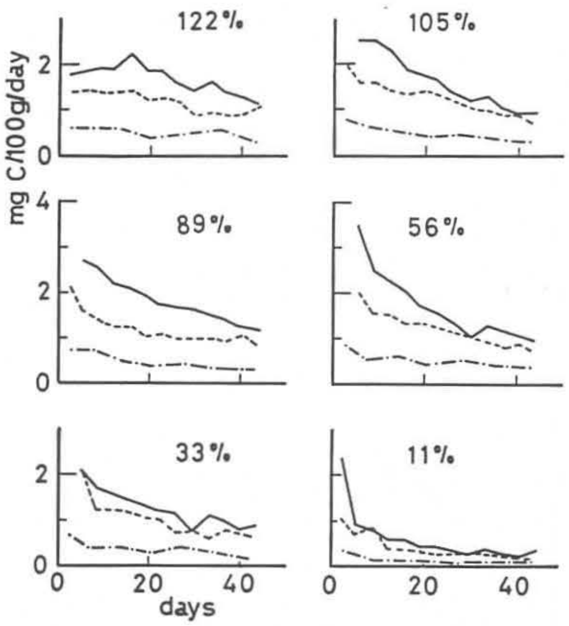

Fig. 11. Time trend curves of the CO_2 evolution rate of Tonegawa Alluvial soil in various water contents at 10°C (— · — · —), 20°C (-----) and 30°C (———).

the sample soil. The curves under the water-logged condition had no initial peaks but in the curves under other conditions there were distinct initial peaks. The CO_2 evolution rates are plotted against the soil water content (Fig. 12). The sample soil had higher CO_2 evolution rates under water-logged condition than under water-saturated condition at each incubation temperature. These higher rates were disregarded as a result of unusual phenomenon, since the reason of this phenomenon was not made clear in this experiment. The maximum evolution rates at 10°, 20° and 30°C and the water contents were 0. 48 mg C/100 g dry soil/day and 56 % (50 % on an oven-dry weight basis), 0. 96 mg C and 89 % (80 %), and 1. 39 mg C and 89 %, respectively. The evolution rates decreased rapidly with the decrease of water content.

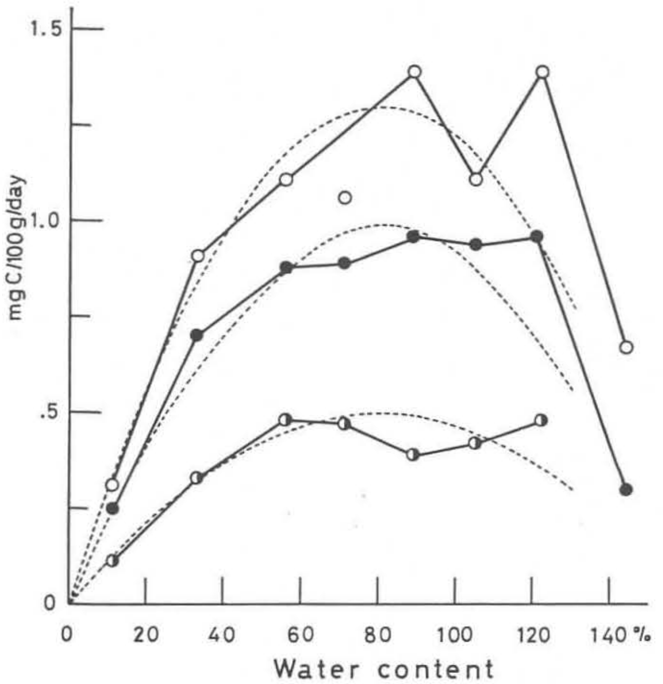

Fig. 12. CO_2 evolution rate in relation to water content with Tonegawa Alluvial soil at 10°C (—◑—), 20°C (—●—) and 30°C (—○—). Broken lines represent approximate curve of relationship between evolution rate and water content at each temperature.

iv) *Koishikawa Kantô Loam soil*

This soil was the same kind as the Chiba soil. The curves of the CO_2 evolution rates plotted against the water contents also resembled those of Chiba soil (Fig. 13). The water contents at the maximum evolution rates were 42 % (50 % on an oven-dry weight basis) at 10°C, 67 % (80 %) at 20°C and 75 % (90 %) at 30°C. The evolution rates were generally lower than those of the Chiba soil: that is, 0. 42, 0. 92 and 1. 12 mg C/100 g dry soil/day at 10°, 20° and 30°C, respectively. This difference of the

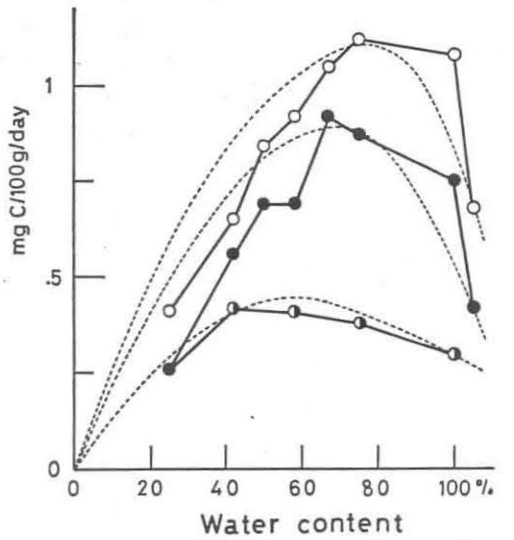

Fig. 13. CO_2 evolution rate in relation to water content with Koishikawa Kantô Loam soil at 10°C (—◑—), 20°C (—●—) and 30°C (—○—). Broken lines represent approximate curve of relationship beween evolution rate and water content at each temperature.

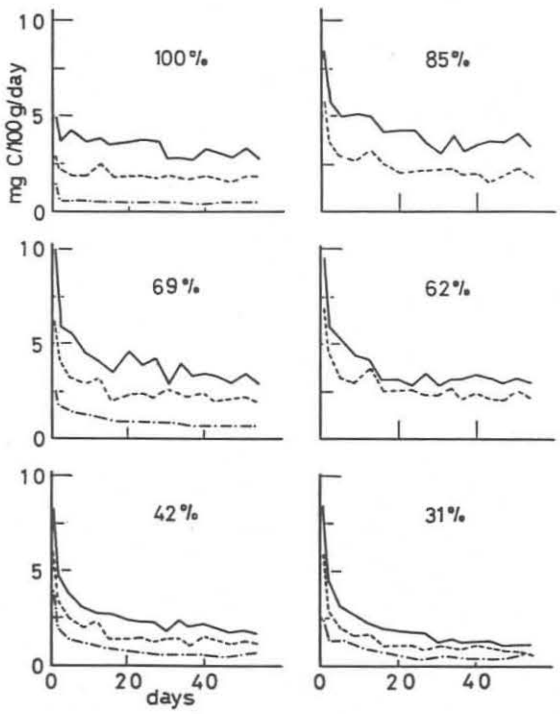

Fig. 14. Time trend curves of the CO_2 evolution rate of Chiba Kantô Loam soil in various water contents at 10°C (—·—·—), 20°C (-----) and 30°C (———).

evolution rates between the Koishikawa and Chiba soils may have been caused by the difference of organic matter properties in both soils.

v) *Chiba Kantô Loam soil*

The time trends of the CO_2 evolution rates are shown in Fig. 14. In water-saturated sample, the curve had low initial peak under each temperature condition, and after that, in a very short period the rates decreased to constant values. Fig. 15 illustrates the CO_2 evolution rates of the sample soil under various water conditions. The water content at the maximum evolution rate was different at each incubation temperature. It was 54 % (70 % on an oven-dry weight basis) at 10°C, 62 % (80 %) at 20°C, and 85 % (110 %) at 30°C. The maximum evolution rate at each incubation temperature was 0.71, 2.31 and 3.68 mg C/100 g dry soil/day, respectively. The gradient of the evolution rates against the water content were very steep, so that a little change of the latter caused a big change of the former. The gradient was largest

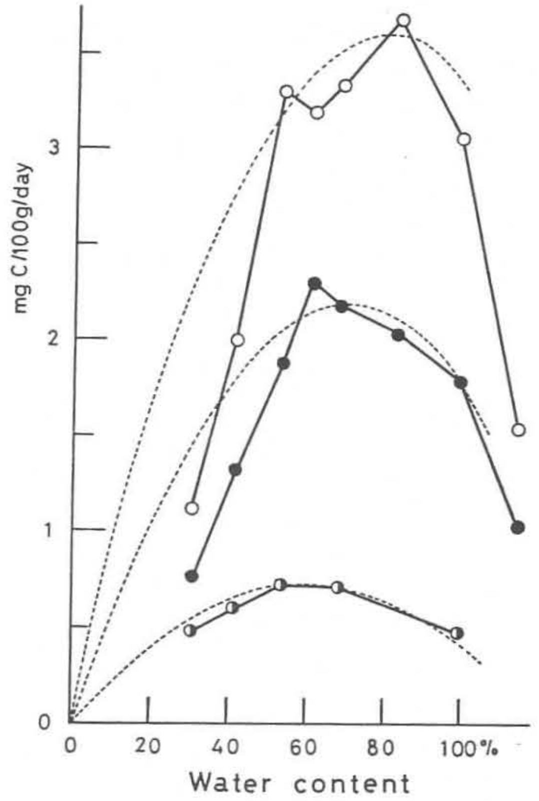

Fig. 15. CO_2 evolution rate in relation to water content with Chiba Kantô Loam soil at 10°C (—◑—), 20°C (—●—) and 30°C (—○—). Broken lines represent approximate curve of relationship between evolution rate water content at each temperature.

at 30°C and smallest at 10°C. The evolution rates were very small under the water condition which caused gleization of the sample soil.

vi) *Futtsu Sandy soil*

The maximum water holding capacity of this soil was very low, i. e. 35 % on an oven-dry weight basis. The water contents at the maximum CO_2 evolution rates were lower than those of the other soils (Fig. 16). The values were 17 % (6 % on an oven-dry weight basis) at 10C°, 51% (18 %) at 20°C, and 26 and 51 % (9 and 18 %) at 30°C. The evolution rates under these conditions were 0. 38, 0. 93 and 1. 39 mg C/100 g dry soil/day, respectively. The time trend curves differed from those of the other soils, especially, the lag period which had been reported by Rovira (45) was recognized.

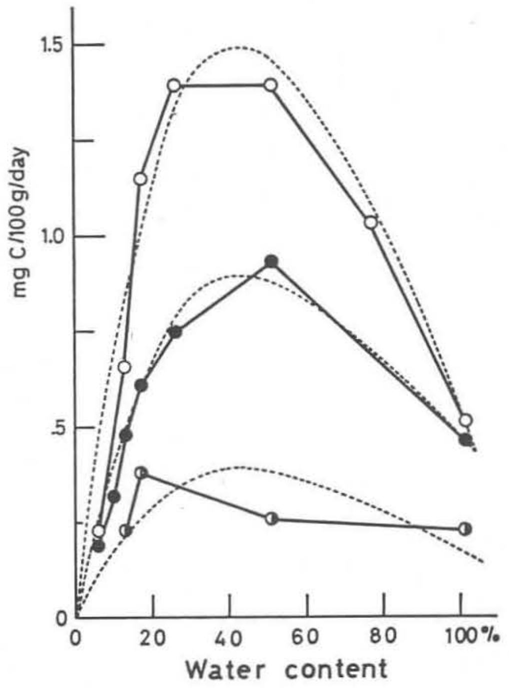

Fig. 16. CO_2 evolution rate in relation to water content with Futtsu Sandy soil at 10°C (—◑—), 20°C (—●—) and 30°C (—○—). Broken lines represent approximate curve of relationship between evolution rate and water content at each temperature.

Reports concerning the exact relation between the CO_2 evolution rate and the soil structure have so far been scanty. In order to treat the diffusion property of oxygen and CO_2 through both gas and water in the limited soil pore, the physical technique seems to be necessary. Letey and his co-workers (28), who had studied the relationship between the growth of plants and oxygen diffusion rate in soil, stated that a

net increase in the rate of oxygen supply was indicated with increased temperature. In the present experiment, the water contents to get the maximum evolution rates at 30° or 20°C were higher than those at 10°C in many sample soils except in the Northern Yatsugatake Brown Forest soil. These experimental results are in good agreement with Letey's report.

The soil structure and microflora are considerably varied by drying of soil. There was remarkable difference between the evolution rate in the untreated soil and that in the air-dried and re-wetted soil. In five types of soil, the evolution rates of the untreated soils corresponded to from two to four times of those of the treated soils that were, after air-drying, regulated by watering to the same water content as the untreated soil.

4. Evolution rate of CO_2 from the subsoil

It is very interesting to study how much CO_2 is produced in the subsoil. In this experiment, subsoils at different depth were taken out and the CO_2 evolution rate was measured with the same method as used for the surface soil. At the same time, several elements in the subsoil were analyzed. Undoubtedly, the rate measured with this method was not normal. In undisturbed soil, a large part of oxygen which diffuses into soil through the surface is to be consumed by microorganisms in the surface soil. As the result of it, oxygen must be insufficient and CO_2 must be accumulated in the subsoil. The quantity as well as quality of organic matter may be different with the depth of soil. Therefore, in order to make the relations between the organic matter conditions and the evolution rates clear, it seems to be available to measure the evolution rates in the soils at different depths.

The CO_2 evolution rates of six sample soils in relation to soil depth are shown in Fig. 17. In all the cases, the evolution rates were larger in the surface soil and decreased to about half at the depth of 5–10 cm. It shows that the properties of soil organic matter varied with the depth and that the deeper it became the less organic matter mineralized. At native soils, the supply of oxygen to soil becomes insufficient at deeper part, so the amounts of CO_2 produced at each depth must be smaller than the rates determined with such a technique.

5. Monthly change of the CO_2 evolution rate

The surface soils under litter horizon were sampled monthly at three stands, Tonegawa, Chiba and Futtsu. The CO_2 evolution rates from these soils were measured at three incubation temperatures of 10°, 20° and 30°C under native water conditions (Table 4).

i) *Tonegawa Alluvial soil*

The CO_2 evolution rates were higher a few times in a year. As a whole the evolution rate in each incubation temperature increased toward summer. The supply of organic matter to the soil was large from September to November. The rates at 10° and 20°C were higher in June than in May but the reversed relation

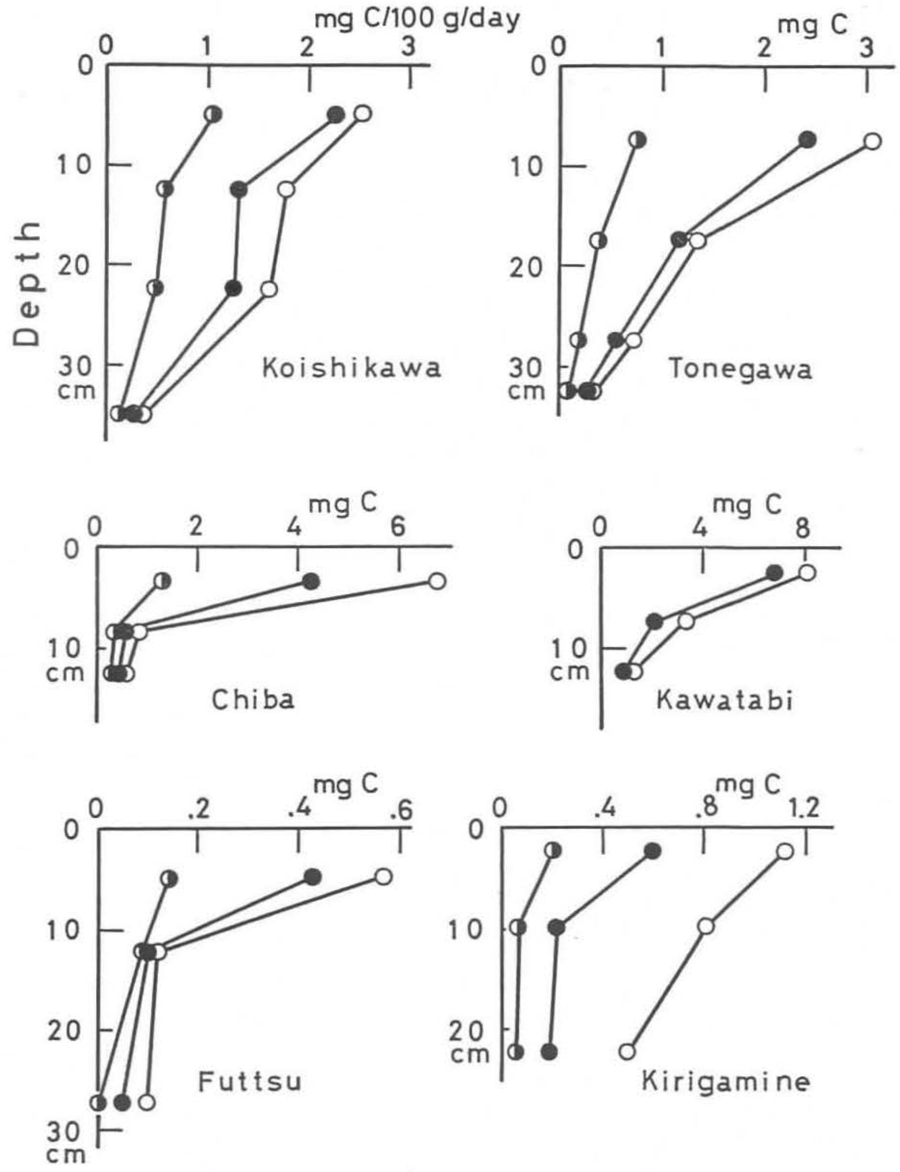

Fig. 17. CO_2 evolution rates of soils sampled from various depths in six stands at 10°C (—◑—), 20°C (—●—) and 30°C (—○—).

was observed at 30°C. It seems that the microorganisms in native soil react to the changes of temperature very complicatedly, because the microflora, the number of microorganisms and their activities must be influenced by temperature variously.

ii) *Chiba Kantô Loam soil*

The CO_2 evolution rates were 1–2 mg C/100 g dry soil/day at 10°C, 4–6 mg C at

Table 4. Seasonal change of CO_2 evolution rates (mg C/100 g dry soil/day) of three types of soil at three incubation temperatures.

Temp.	1965 Oct.	Nov.	Dec.	1966 Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Tonegawa Alluvial soil														
10°C	0.73	0.93	0.82	0.90	0.89	1.20	1.23	1.15	1.34	1.01	0.87	0.62	—	—
20°	2.00	3.12	2.26	2.68	2.36	3.14	3.70	3.62	4.38	3.41	3.92	2.25	—	—
30°	3.00	4.01	3.62	3.58	3.50	3.78	4.84	4.95	4.69	4.18	6.91	3.07	—	—
Chiba Kantô Loam soil														
10°C	—	—	1.33	1.56	1.60	1.53	1.95	1.83	1.36	2.60	1.01	0.64	1.37	1.61
20°	—	—	4.28	4.31	5.06	4.36	6.03	7.37	5.79	12.64	3.92	1.97	5.72	5.00
30°	—	—	6.80	6.57	7.34	6.18	8.85	10.84	7.78	14.60	5.98	3.22	9.44	7.30
Futtsu Sandy soil														
10°C	0.20	0.27	0.20	0.34	—	1.25	0.35	0.42	0.19	0.32	0.06	0.11	0.12	—
20°	0.81	0.71	0.52	0.63	—	4.10	1.21	2.17	0.90	1.23	0.22	0.53	0.55	—
30°	0.84	1.29	0.82	1.14	—	6.06	1.62	3.47	1.01	1.66	0.40	0.84	0.60	—

20°C, and 6–10 mg C at 30°C, through a year. In July the evolution rate was the largest at each incubation temperature, with soil water content at its optimum (Table 3, Fig. 15). The organic carbon and total nitrogen contents in July were little different from those in August. This suggests that the soil water content has larger influence on the CO_2 evolution rate than the organic matter content. The amount of litter fall was large in May, October and November. Pine leaves and twigs fell in May and *Miscanthus* and *Imperata* withered towards the end of autumn.

iii) *Futtsu Sandy soil*

The CO_2 evolution rates were low in general, but in March strikingly high peaks appeared at all incubation temperatures, when the highest contents of organic carbon and of water and the lowest pH (H_2O) value in the year were observed. These results showed that the content of organic matter was very high in March, nevertheless a maximum litter fall usually occurred in April and May. Some irregular supply of fresh organic matter would be considered as a reason of this phenomenon. It was certain that the increase of the evolution rate in May was caused by the regular fresh litter supply. The mineralization of fresh organic matter quickens the mineralization of accumulated organic matter. This phenomenon has been studied by some workers as "Priming action" (7, 22, 46, 50, 51). The depression of the evolution rate in August, 1966 was caused by the unusual drought. As shown in Table 3, the fluctuation in water content of this soil was larger than that of the other soils.

To examine the seasonal change of microbial activity in the following three types of soil, Tonegawa soil, Chiba soil and Futtsu soil, the increase of the CO_2 evolution rate with increase of temperature by 10°C was calculated each month. The increasing rate from 10°C to 20°C was expressed as $\left(R_{10}^{10-20}\right)$, and the rate from 20°C to 30°C, $\left(R_{10}^{20-30}\right)$. Monteith *et al.* (36) reported that the rate was 3 from the result

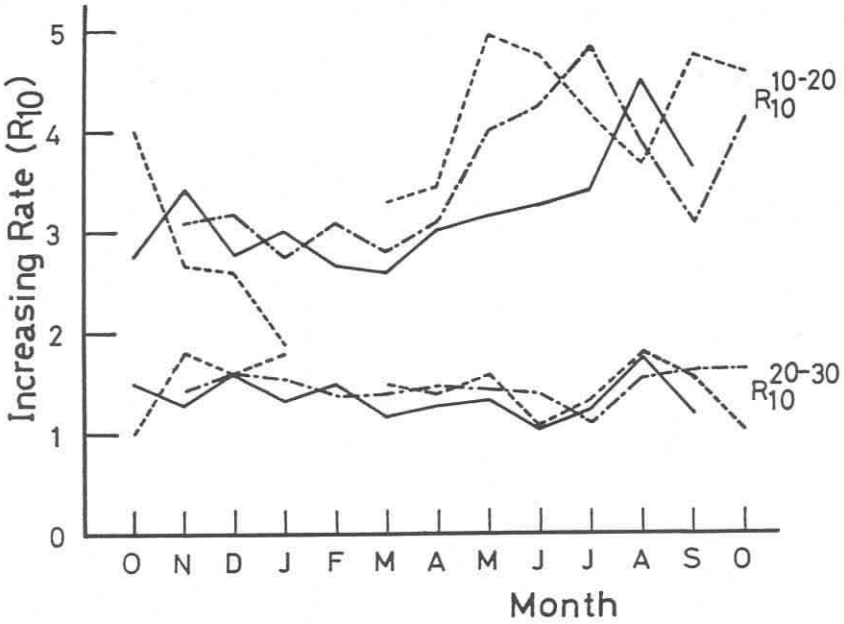

Fig. 18. Seasonal change of the increase rate of the CO_2 evolution with the increase of temperature by 10°C.
Tonegawa Alluvial soil (————)
Chiba Kantô Loam soil (— · — · —)
Futtsu Sandy soil (--------)

of field measurment from September to January in Great Field II. As shown in Fig. 18, $\left(R_{10}^{10-20}\right)$ was larger than 2 at three stands through a year, while $\left(R_{10}^{20-30}\right)$ was smaller than 2. The former was larger than the latter through a year. This apparently indicated that the temperature of 30°C was near the optimum for microbial activities. In all the sample soils, the difference between both rates was smaller in winter than in summer, because $\left(R_{10}^{10-20}\right)$ became larger in summer but $\left(R_{10}^{20-30}\right)$ remained roughly constant through a year in each sample soil. This summer increase might be caused by the changes of the microbial activity and microflora with the increase of temperature and the progress of decomposition of soil organic matter. These phenomena show that even a change of temperature gives rise to a complexity of reactions in soil.

DISCUSSION

1. Relation between the CO_2 evolution rate and soil properties

The two relations of the CO_2 evolution rates at 30°C to the content of organic carbon, and to total nitrogen in surface soil are shown in Figs. 19 and 20, respectively. Soils rich in humus contained both elements more than the other soils did.

As shown in Fig. 19, the CO_2 evolution rate of Kirigamine soil containing organic carbon of 19 % on an oven-dry weight basis was approximately the same as

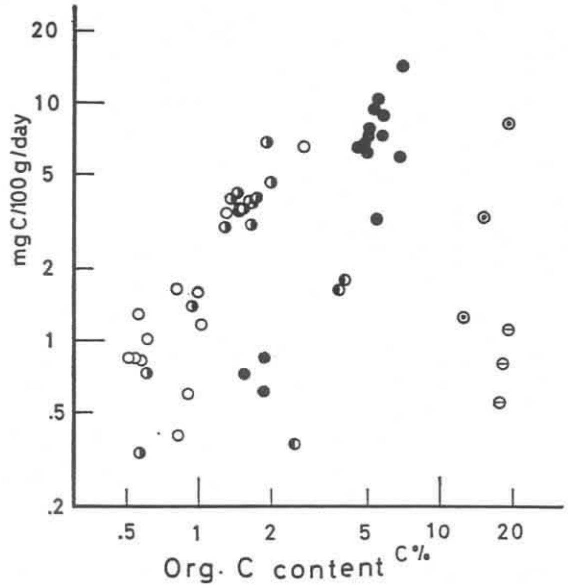

Fig. 19. CO_2 evolution rates of Kawatabi soil (◉), Kirigamine soil (⊖), Tonegawa soil (◑), Chiba soil (●), Koishikawa soil (◐), and Futtsu soil (○) at 30°C in relation to the organic carbon content of these soils.

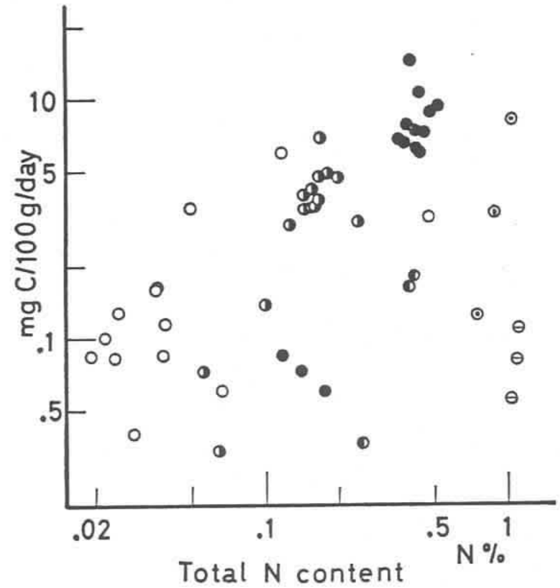

Fig. 20. CO_2 evolution rates of Kawatabi soil (◉), Kirigamine soil (⊖), Tonegawa soil (◑), Chiba soil (●), Koishikawa soil (◐), and Futtsu soil (○) at 30°C in relation to the total nitrogen content of these soils.

that of Futtsu soil which contained organic carbon less than 1 %. The relation of the evolution rate to the organic carbon content in each soil could be expressed with a straight line with a different gradient. There were some reports that the speed of carbon mineralization was directly related to the organic carbon content of soil (1, 31), but in other report (6) the loss rate of organic carbon had no correlation to total carbon content. In the present study, the CO_2 evolution rate was proportional to the organic carbon content only in the soil from the same stand. Among the soils from the different stands, no correlations were observed.

The sample soils that had high CO_2 evolution rate contained large amount of total nitrogen (Fig. 20). This correlation was weaker than the correlation between the evolution rate and organic carbon content, though it was already reported that the amount of nitrogen controls the mineralization of soil organic matter and litter (2, 33, 44, 57).

Between the CO_2 evolution rate and the total phosphorus content no clear relation was obtained.

The relation between the CO_2 evolution rate and the pH value was not made clear, though for the evolution an optimum pH 7 or so was reported (1, 3).

The CO_2 evolution rate (R_E) can be calculated with the following function in consideration of many environmental factors (X_1, X_2, $X_3 \cdots\cdots$) :

$$R_E = f(X_1,\ X_2,\ X_3 \cdots\cdots).$$

Considering underground temperature (T°C), water content (W%) and organic carbon content (C%) as main factors which influence the activity of soil organisms, we can change the above equation as follows :

$$R_E = f(T,\ W,\ C).$$

The CO_2 evolution rate, in parallel with organic carbon and total nitrogen contents, decreased with the depth of soil profile. The linear relationships between the evolution rate and the organic carbon content at incubation temperatures of 10°, 20° and 30°C are shown in Fig. 21. The relationships are expressed by the following equations :

For Tonegawa soil : $$R_E = \frac{-1.08}{200}(T^2 - 63T + 370)(C - 0.43),$$

Chiba soil : $$R_E = \frac{-0.22}{200}(T^2 - 83T + 532)(C - 1.50),$$

Futtsu soil : $$R_E = \frac{-0.36}{200}(T^2 - 70T + 400)(C - 0.05),$$

Koishikawa soil : $$R_E = \frac{-0.30}{200}(T^2 - 63T + 333)(C - 2.15),$$

where R_E is CO_2 evolution rate (mg C/100 g dry soil/day) ; T, incubation temperatures in °C ; and C, organic carbon percentage of the soil on an oven-dry weight basis.

The relations between the CO_2 evolution rate and the water content in the six

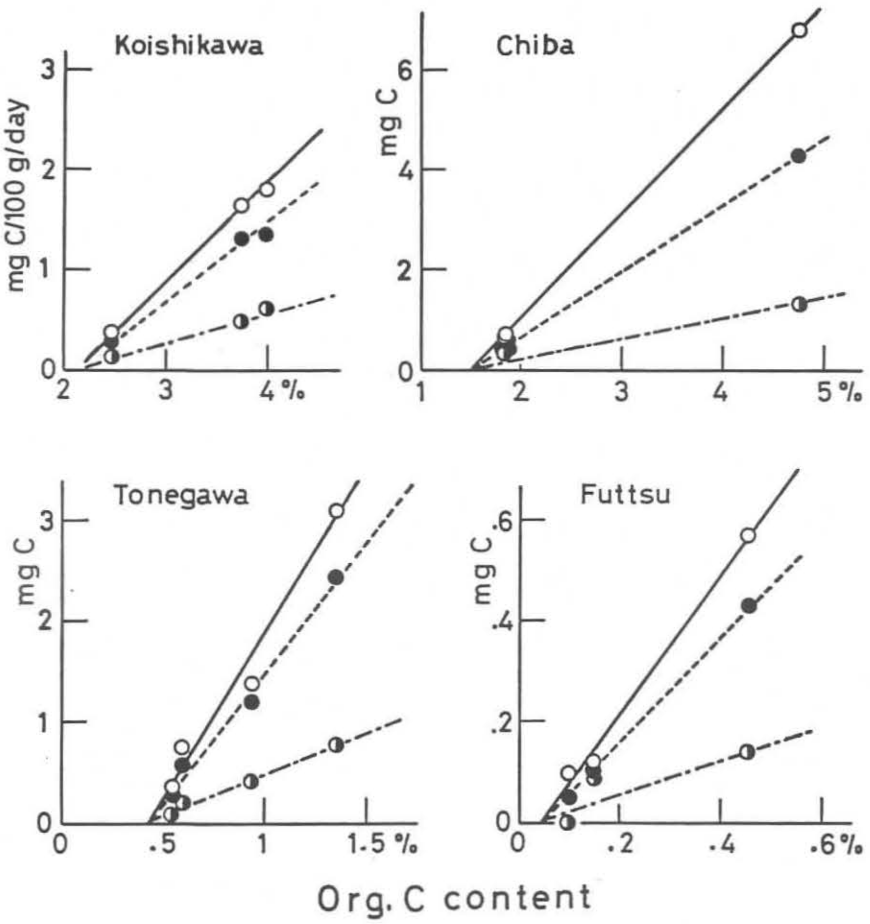

Fig. 21. Relationship between the CO_2 evolution rates of soils sampled from various depths at 10°C (—◑—), 20°C (—●—) and 30°C (—○—), and the organic carbon contents in each sample soil.

soils shown in Figs. 9, 10, 12, 13, 15 and 16 could be, though quite roughly, expressed with common parabolas, broken lines in the figures, at each incubation temperature. The CO_2 evolution rates at very low or high water contents were off these curves but such extreme water conditions did not occur normally in nature. Interposing temperature term, the equations of these parabolas were set up as follows :

Kirigamine soil : $R_E=\frac{-1}{200}(T^2+2T+16)\frac{W}{170}\left(\frac{W}{170}-1\right)$,

Northern Yatsugatake soil : $R_E=\frac{5.0}{200}(T^2-90T+600)\frac{W}{160}\left(\frac{W}{160}-1\right)$,

Tonegawa soil : $R_E=\frac{0.8}{200}(T^2-80T+200)\frac{W}{160}\left(\frac{W}{160}-1\right)$,

Chiba soil : $$R_E=\frac{0.9}{200}(T^2-103T+600)\frac{W}{100+2T}\left(\frac{W}{100+2T}-1\right),$$

Koishikawa soil : $$R_E=\frac{0.9}{200}(T^2-69T+200)\frac{W}{100+2T}\left(\frac{W}{100+2T}-1\right),$$

Futtsu soil : $$R_E=\frac{-0.4}{200}(T^2+70T)\frac{W}{80}\left(\frac{W}{80}-1\right).$$

These equations were set up with air-dried soil, so that with undried soils their constants must be changed.

With untreated soils at the Tonegawa, Chiba and Futtsu stands, the following equations were obtained :

Tonegawa soil : $$R_E=\frac{5.8}{200}(T^2-64T+379)\frac{W}{160}\left(\frac{W}{160}-1\right)(C-0.57),$$

Chiba soil : $$R_E=\frac{7.7}{200}(T^2-163T+933)\frac{W}{160}\left(\frac{W}{160}-1\right)(C-2.16),$$

Futtsu soil : $$R_E=\frac{2.2}{200}(T^2-70T+400)\frac{W}{80}\left(\frac{W}{80}-1\right)(C-0.46),$$

where C means organic carbon content. In Table 5, the calculated values at 10°, 20° and 30°C are shown. If they are compared with the measured values (Tablea 4), there were some differences between both values through a year. These differences may have been caused by the untouched factors in the present study, that, is, the structure of soil, the properties of organic matter, the species and activities of soil organisms, etc. The more complex are the properties of organic matter and the soil structure, the larger are these differences.

2. Calculation of annual CO_2 flux from soil surface

In order to calculate the CO_2 amount evolved from the soil surface at each stand

Table 5. CO_2 evolution rate (mg C/100 g dry soil/day) calculated from temperature, water content and organic carbon content (cf. Table 4).

Temp	1965 Oct.	Nov.	Dec.	1966 Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
						Tonegawa Alluvial soil								
10°C	0.69	0.80	0.99	0.92	0.87	1.08	1.04	1.18	1.52	0.96	1.25	0.95	—	—
20°	2.17	2.49	3.07	2.87	2.73	3.38	3.25	3.69	4.76	3.00	3.86	2.99	—	—
30°	2.77	3.18	3.93	3.66	3.49	4.33	4.16	4.72	6.08	3.84	5.02	3.82	—	—
						Chiba Kantô Loam soil								
10°C	—	—	1.33	1.26	1.77	1.44	1.82	1.81	1.49	2.65	1.82	1.21	1.44	1.43
20°	—	—	4.28	4.05	5.21	4.57	5.83	5.83	4.80	8.56	5.89	3.88	4.64	4.63
30°	—	—	6.80	6.42	9.06	7.33	9.30	9.25	7.61	13.55	9.33	6.16	7.05	7.03
						Futtsu Sandy soil								
10°C	0.15	0.24	0.17	0.34	0.14	0.69	0.40	0.49	0.27	0.36	0.13	0.11	0.25	—
20°	0.45	0.71	0.53	1.04	0.43	2.06	1.20	1.50	0.83	1.08	0.40	0.34	0.73	—
30°	0.61	0.96	0.70	1.40	0.57	2.75	1.61	2.00	1.10	1.44	0.53	0.47	0.98	—

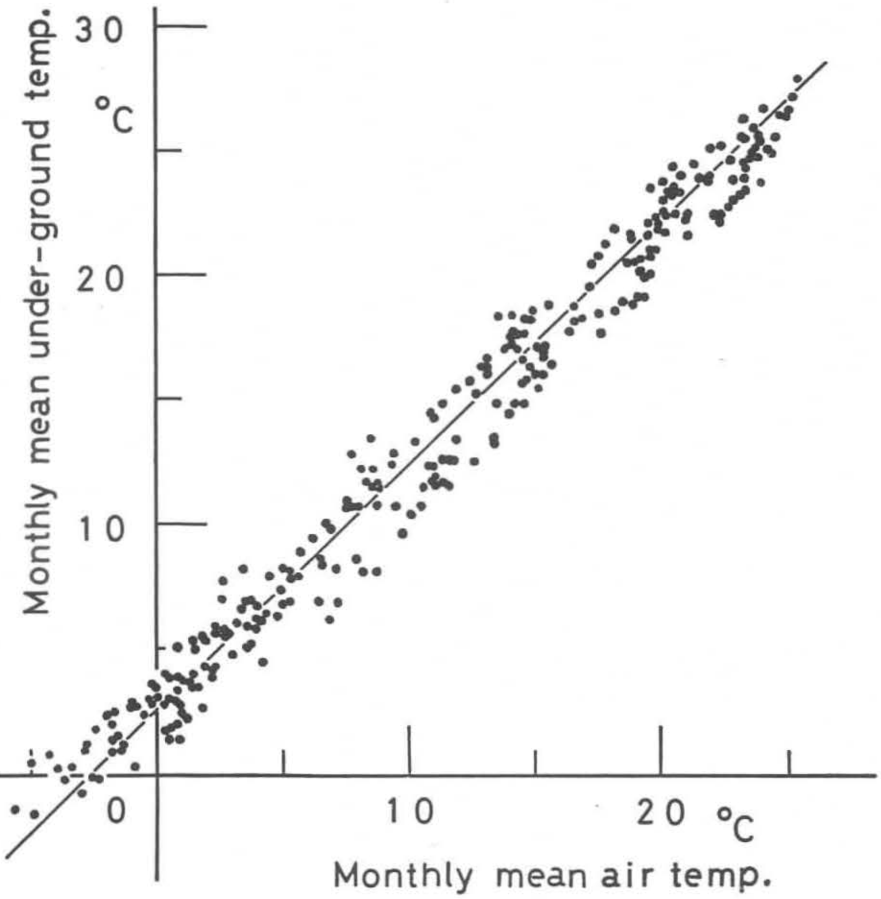

Fig. 22. Relationship between monthly mean air temperature and monthly mean underground temperature at 30 cm depth at 23 meteorological stations in Japan.

the corresponding data of underground temperature are necessary. The daily change of the 30 cm-underground temperature in a tall grass community was similar to that of the 5 cm-underground temperature in a short grass community and in bare land, in summer at Kirigamine and Kawatabi grasslands. Monthly mean underground temperature at 30 cm depth was estimated from air temperature. Both mean temperatures at 23 meteorological stations in Japan were picked up from climatological tables. The relation betweem them could be expressd with a straight line (Fig. 22). This equation was $Tu=0.97T_a+2.51$. 'Tu' is monthly mean underground temperature at 30 cm depth and 'Ta' is monthly mean air temperature.

For the calculation of the amount of CO_2 evolved from litter the surface temperature is necessary. In the same way as is mentioned above, the relation between monthly mean surface temperature 'Ts' and air temperature was set up. When the

stations were under 100 m in altitude, the equation became $T_S=1.12\,T_a$ ($T_S>0$). In the case of above 100 m, the equation was $T_S=1.12\,T_a+0.45$ ($T_S>0$).

Monthly fluxes of CO_2 in three stands, Tonegawa, Chiba and Futtsu, were calculated with the equation $R_E=f(T,\ W,\ C)$. Monthly mean water content (W) and mean organic carbon content (C) were estimated from analyzed values in each month. In this calculation, it was assumed that 60 % of total flux was produced in soil from surface to 5 cm depth and 90 % was produced in the soil from surface to 10 cm depth. Soil volume was estimated with volume weight data in several profiles. The calculated results are shown in Table 6.

Table 6. Monthly change of CO_2 evolution amounts (g C/m²/month) of soil and litter at Tonegawa, Chiba and Futtsu stands.

Month	Tonegawa		Chiba		Futtsu	
	soil	litter	soil	litter	soil	litter
Jan.	—	—	8	—	4	—
Feb.	—	—	4	—	2	—
Mar.	6	—	18	4	19	10
Apr	29	8	53	14	31	16
May	49	11	72	15	60	22
Jun.	73	20	80	22	57	21
Jul.	58	22	144	19	48	14
Aug.	66	68	120	20	20	22
Sep.	53	58	72	11	14	24
Oct.	30	99	83	18	16	14
Nov.	20	54	33	11	15	6
Dec.	14	—	10	3	7	2
Total	398	340	697	137	293	151

The CO_2 flux from soil without litter was influenced remarkably by its water content and it was large in summer, i.e. 1.5–5 g C/m²/day. The annual flux from the horizon of 10 cm depth was estimated to be 398 g C/m² at the Tonegawa stand, 697 g C at the Chiba stand, and 293 g C at the Futtsu stand.

The amount of CO_2 evolved from soil surface is the sum total of CO_2 produced by soil organisms, especially by microbes, in soil and litter, by plant roots and by chemical reactions. The CO_2 amount evolved by respiration of plant roots can vary widely according to their conditions and it is very difficult to measure the root respiration under the natural condition. So it may be rather preferable to eliminate root respiration from the purpose of the present study. The CO_2 amount evolved by chemical reactions seems to be negligibly small under the normal condition in noncalcareous soil. It was stated that in the carbonate horizon, the large CO_2 amount was liberated at a low moisture content such as about wilting moisture (58).

A large CO_2 amount can be evolved from the accumulated litter on the soil surface. Judging from the absorption of oxygen by litter, Bloomfield (5) stated that the decomposition was much faster in the litter horizon than in the soil horizon. The

present authors measured the CO_2 evolution rate from litter with the same way as from the soil. Under the thoroughly wet conditions the evolution rate was very high. The relation between the evolution rate and temperature could be expressed with the following equations:

Tonegawa litter : $R_E=-0.3(T^2-87T+633)$,

Chiba litter : $R_E=-0.3(T^2-73T+467)$,

Futtsu litter : $R_E=-0.3(T^2-60T+367)$.

The CO_2 evolution rate from litter was influenced considerably by the water condition as reported by several workers (11, 65, 67). In comparison with the rates under natural conditions, the calculated rates should be overestimated, because native litter was often dried up. Therefore, it was assumed that the actual CO_2 evolution amount from litter was one third of the calculated values at the Tonegawa and Chiba stands and quarter at the Futtsu stand where litter was often dried up severely. The CO_2 amounts from litter are summarized in Table 6. The annual total of CO_2 fluxes from soil and litter was 738 g C/m^2 at Tonegawa, 834 g C at Chiba and 444 g C at Futtsu stand.

Provided the carbon content in litter was 45 % of dry weight, annual supplies of organic carbon to soil were 801 g/m^2 at the Tonegawa stand (21), 540 g at the Chiba stand, and 477 g at the Futtsu stand (23). The calculated flux value is larger than the annual supply at Chiba, but at the Tonegawa and Futtsu stands they were in good agreement.

Wegert and Evans (64) reported with studying on an Old Field in southeastern Michigan that the dead material on the field disappeared at a rate of 187–29 mg C/100 g dry litter/day on the upland, and 303–40 mg C on the swales, depending on time of year.

Annual CO_2 flux from the soil at the other four stands, Kirigamine, Northern Yatsugatake, Koishikawa and Kawatabi, was calculated with the equation $R_E=f(T)$. The amounts were 33, 330, 280 and 259 g C/m^2, respectively. The CO_2 amount evolved from litter was added to the above values. The annual flux of 74 g C/m^2 at the Kirigamine stand was very small compared with that of 374 g C at the Northern Yatsugatake stand. The reasons seem to be the property of organic matter, low pH values, etc.

SUMMARY

The CO_2 amount evolved from soil was measured experimentally by the closed box method, so as to calculate the annual CO_2 evolution amount from field soils on the basis of the obtained data and the rough estimation of several factors, temperature, moisture and organic carbon content of the soils.

1) The following soils were used in the experiment: i) Kawatabi Humic Allophane soil, ii) Kirigamine Humic Allophane soil, iii) Northern Yatsugatake Brown Forest soil, iv) Tonegawa Alluvial soil, v) Koishikawa Kantô Loam volcanic ash soil, vi) Chiba Kantô Loam volcanic ash soil, and vii) Futtsu Sandy soil.

2) Special apparatus for measuring CO_2 evolved from soil sample was made by combining large and small plastic containers. An examination proved that this apparatus could be used for this investigation. The value used as the CO_2 evolution rate is a mean value of that obtained during 4–7 weeks after incubation.

3) The CO_2 evolution rates were measured in the dark at three incubation temperatures, 10°, 20° and 30°C, and various water contents of the soil. The rate attained their maximum when the water content was 40–80 % of maximum water holding capacity. The CO_2 evolution rates at 20°C and optimum water content were 0. 63 mg C/100 g dry soil/day in Kirigamine soil; 4. 90 mg in Northern Yatsugatake soil; 0. 96 mg in Tonegawa soil; 0. 92 mg in Koishikawa soil; 2. 31 mg in Chiba soil; and 0. 93 mg in Futtsu soil. The effect of water content on the CO_2 evolution rate was expressed with a common parabola. The relation between the evolution rate and incubation temperature from 10° to 30°C was also expressed with a common parabola.

4) A linear relation existed between the CO_2 evolution rate and organic carbon content in each soil, but the relation between the evolution rate and total nitrogen content was weak.

5) In consideration with temperature (T°C), water content (W%) and organic carbon content (C%) of the soil, the CO_2 evolution rate (R_E mg C/100 g dry soil/day) was expressed with the following function:

$R_E=f(T,\ W,\ C)$.

Real values obtained with the soil samples were discussed.

6) Annual CO_2 evolution amounts in three stands, Tonegawa, Chiba and Futtsu, were calculated with the function $f\ (T,\ W,\ C)$, and for the other fields, the function $f\,(T)$ was used. Relations between monthly mean air temperature and underground temperature or surface temperature were expressed by linear equations.

7) The CO_2 amounts evolved from the soil surface (without litter) were calculated to be 398 g C/m² in the Tonegawa stand, 697 g C in the Chiba stand, 293 g C in the Futtsu stand, 33 g C in the Kirigamine stand, 330 g C in the Northern Yatsugatake stand, 259 g C in the Kawatabi stand, and 280 g C in the Koishikawa stand.

8) The CO_2 amount evolved from litter was calculated and added to the amount evolved from the soils. The CO_2 annual evolution amounted to 738 g C/m² at the Tonegawa stand, 834 g C at the Chiba stand, 444 g C at the Futtsu stand, 74 g C at the Kirigamine stand, and 374 g C at the Northern Yatsugatake stand. These values were compared with supply of organic carbon from the plant community growing in each station.

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